Can DIS guide us into the “Challenging” Higher-W Resonance Region?

What can we learn from Quark-Hadron DUALITY?

NuSTEC Workshop on Pion Production in the Resonance Region
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Fermilab

Define (Pragmatically) Non-Resonant + Resonant Meson Production as Shallow Inelastic Scattering (SIS)

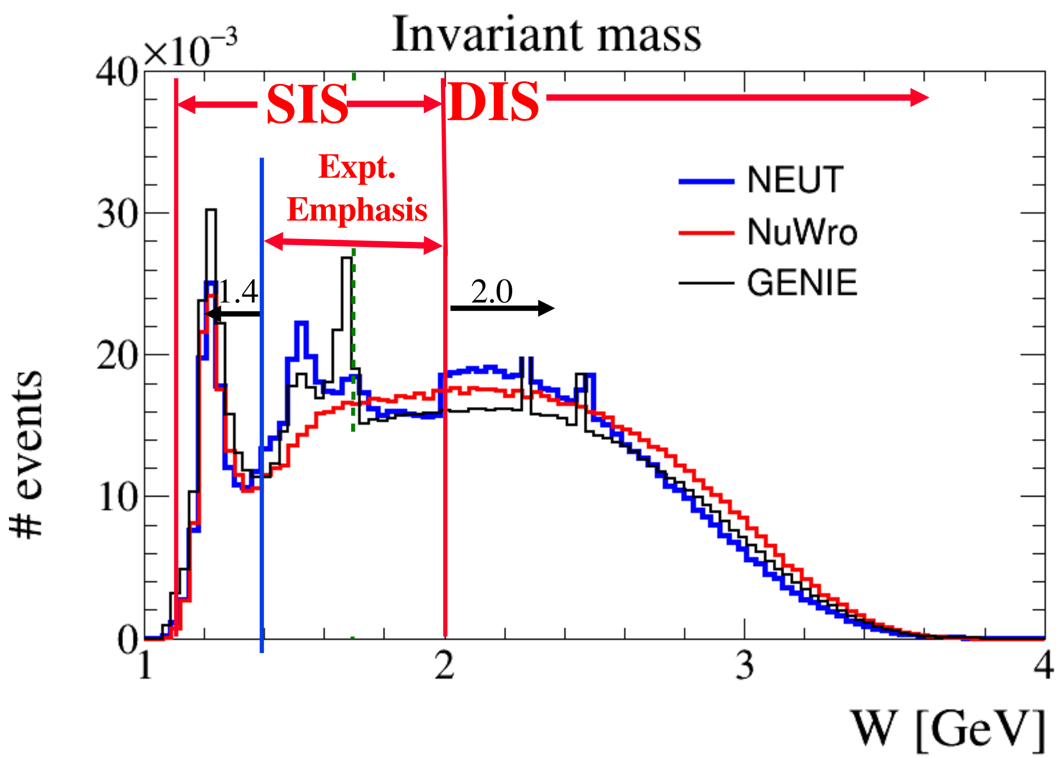
The General **SIS/DIS** Landscape – Comparison of Generators

- By far the majority of contemporary studies in ν-nucleus interactions have been of Quasielastic and Δ production - that is $W \leq 1.4$ GeV

- However, there is plenty of activity going on above this W cut!

$1.4 \text{ GeV} \leq W \leq 2.0 \text{ GeV}$

For example with a 6 GeV ν on Fe – excluding QE.



C. Bronner- 2016

The SIS $\longleftrightarrow$ DIS Transition!

- How does the SIS region transition to DIS?
  - How does the physics (language) of quark/partons from DIS meet the physics of nucleons/pions of SIS $\rightarrow$ **quark-hadron duality**
  - Do the nuclear effects measured in the DIS region extend down into the SIS region or do they suddenly/slowly turn off.

- How do we study it? **MINERνA starting the high-statistics expt. study!**
  - The Δ has been relatively thoroughly studied. **Measure single/multiple pion production in the kinematic region 1.4 < W < 2.0 GeV**
  - Measure total and differential inclusive cross sections with ξ , Q^2 and W in the SIS region off various nuclei. How do they transition into the DIS regime?
  - Compare the cross sections derived in the DIS with the SIS equivalents.
  - With both ν and $\bar{\nu}$ extract the SIS structure functions $F_i(_i\ \xi, Q^2)$ and compare to DIS F_i
  - Determine nuclear effects by ratios of σ off nuclei in the SIS region…

Neutrino interactions in resonance region beyond $\Delta(1232)$ is much more difficult to understand than in $\Delta(1232)$ region

S. Nakamura, "Dynamical coupled-channels approach to Resonance Region beyond Δ(1232)"

	$\Delta(1232)$ region	Beyond $\Delta(1232)$ region ($W \lesssim 2$ GeV)
Resonance	$\Delta(1232)$ dominates No other resonances	No single resonance dominate Several comparable resonances overlap
Non-resonant	Much smaller than $\Delta(1232)$ ChPT works → well-controlled	Comparable to resonant contributions ChPT not work
Relative phases among mechanisms	(fairly) well-controlled	Crucially important but not easy to control
Coupled-channels	Only πN	πN and $\pi\pi N$ are comparable and strongly coupled ηN, $K\Lambda$, $K\Sigma$ channels are also coupled

We are here to compare notes on this region

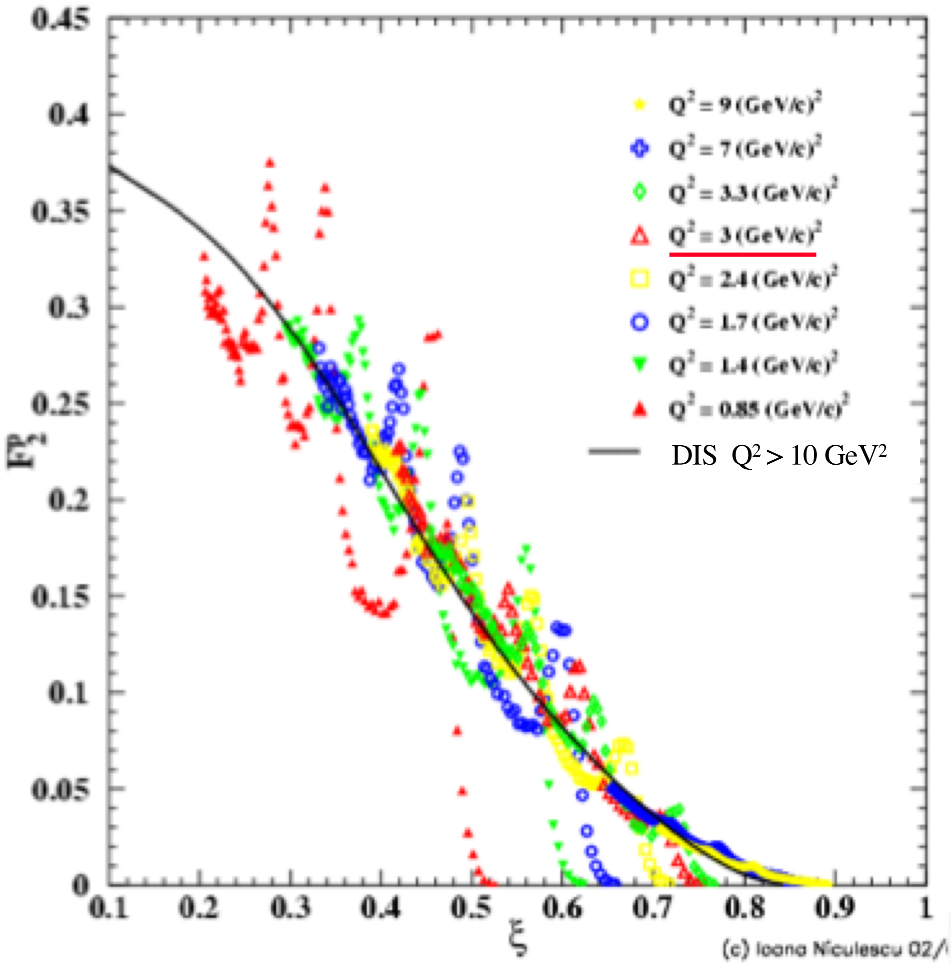
Inclusive SIS studies and "Quark-Hadron Duality"

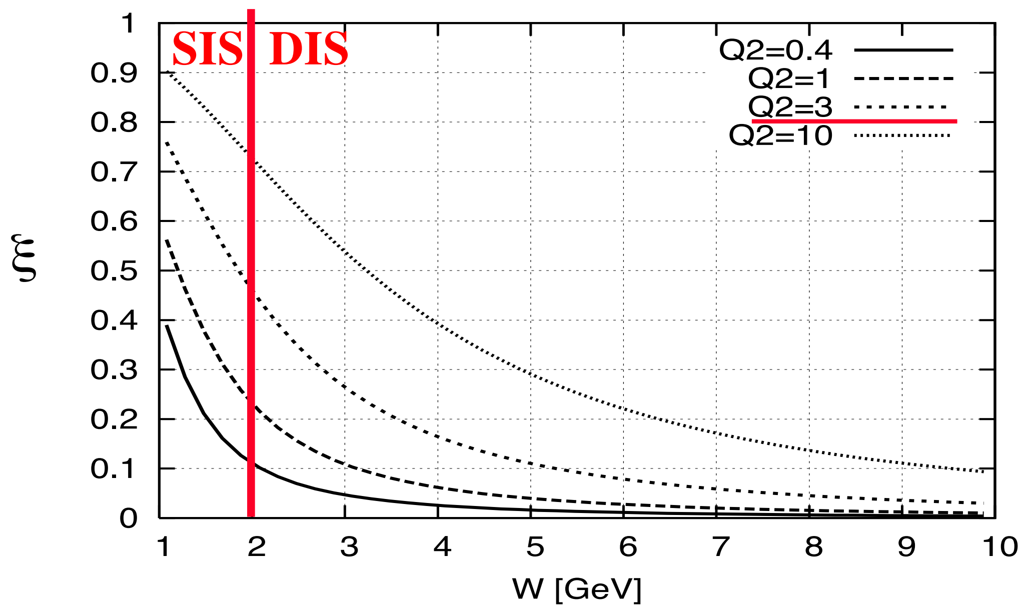
- Quark–hadron duality is a general feature of strongly interacting landscape.
  - Relationships between meson–nucleon and quark–gluon degrees of freedom.
- In the 60's the concept of "Duality" began with the total pion-proton cross section being compared to Regge fits to higher energy data and concluding low-E hadronic cross sections on average could be described by high-energy behavior.
- In the 70's Bloom and Gilman defined duality by studying structure functions from e-N scattering and noting that the leading QCD formulation of DIS is approximately equal to the average over resonance production
- Quark-hadron duality originally studied and confirmed in e-N scattering – how about ν-N scattering?

- There is essentially no high-statistics ν-N/A experimental data with $1.4 < W < 2.0$ GEV for tests! **MINERνA is working to fix this for $\nu/\bar{\nu}$-A!**

- **For now we rely on theoretical models of this region for both an assessment of duality in ν-N/A scattering. …<u>and an evaluation of the models?</u>**

What does Global Q-H Duality “Look Like” Experimentally?
Early Jefferson Lab 6 GeV - e-Nucleon Study





$$\xi = \frac{2x}{\left(1 + \sqrt{1 + 4m_N^2 x^2 / Q^2}\right)}$$

So-called Nachtmann variable to account for Target Mass Effects

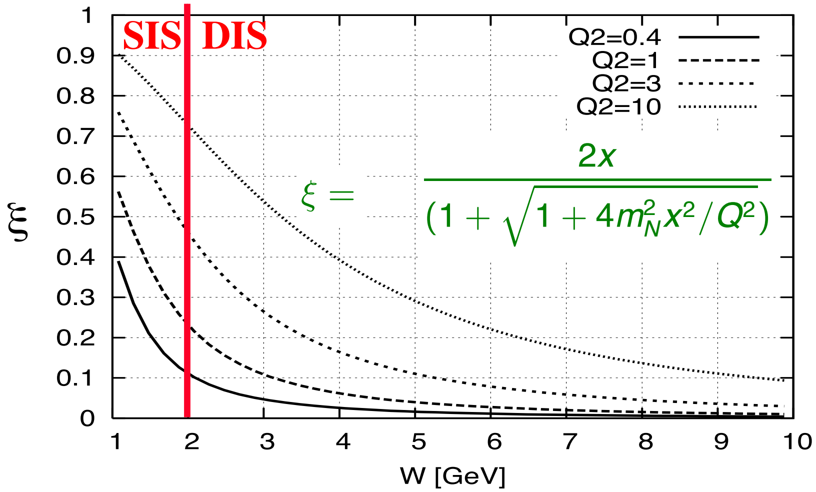
Quantitative test of Quark-Hadron - Local Duality:

Ratio of integrals over a finite ξ interval

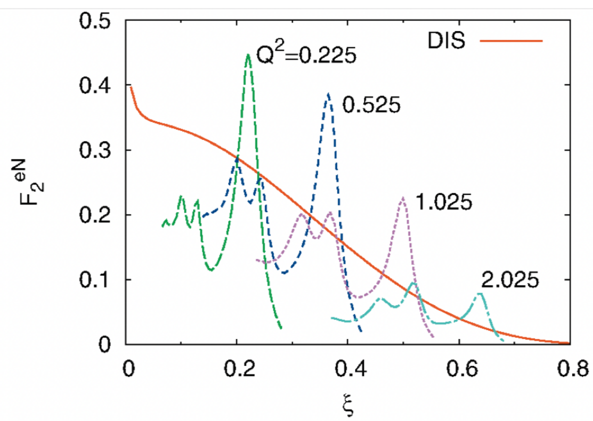
e - Nucleon

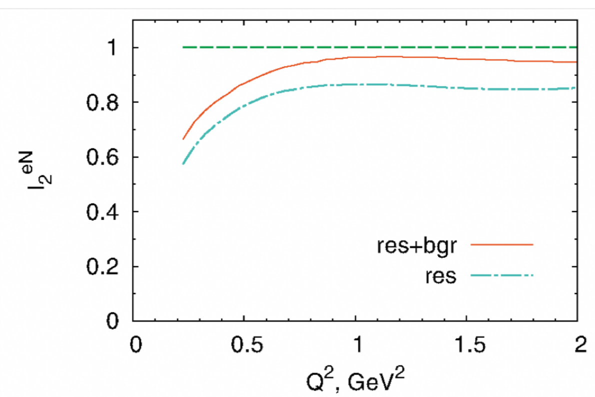
- Ratio of the strength of the SIS to DIS region. Ideal Duality I = 1.0

$$\mathcal{I}_{|}(Q^2, Q^2_{DIS}) = \frac{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{RES}(\xi, Q^2)}{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{DIS}(\xi, Q^2_{DIS})}$$



- Using Giessen fit to e-N scattering – $F_2^{eN}(\xi)$ for values of Q^2 indicated on spectra compared to LO DIS QCD fit at Q^2 = 10 GeV^2. Value of integral I(Q^2).

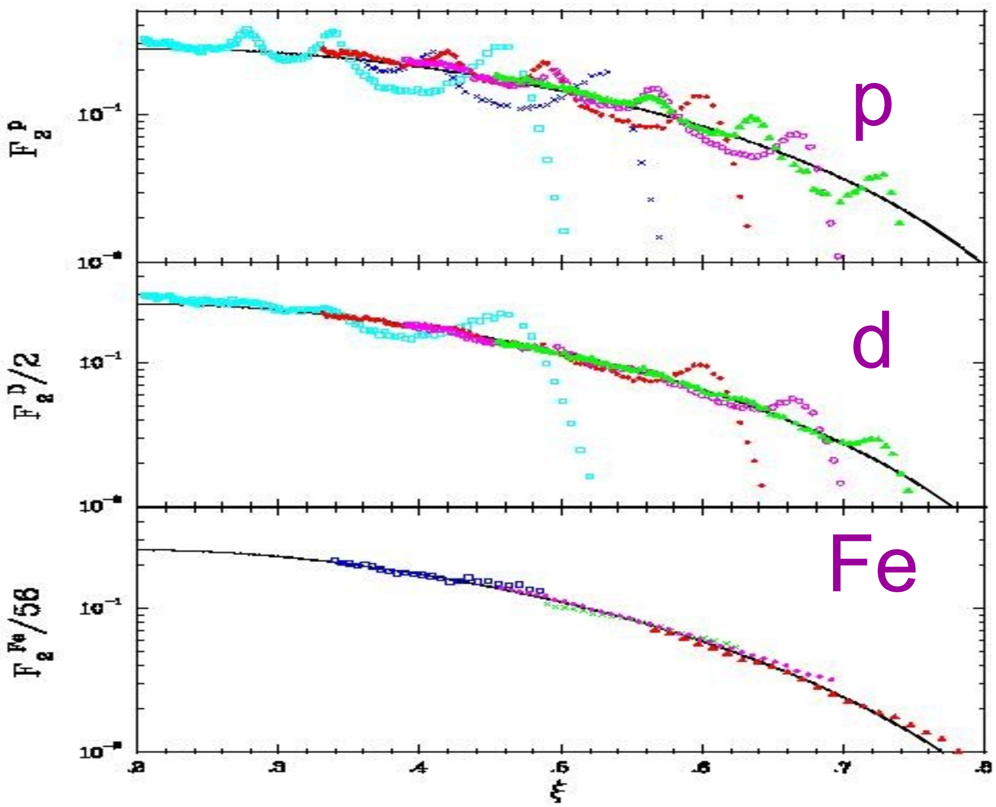




Stress the importance of including the **non-resonant** pion production!

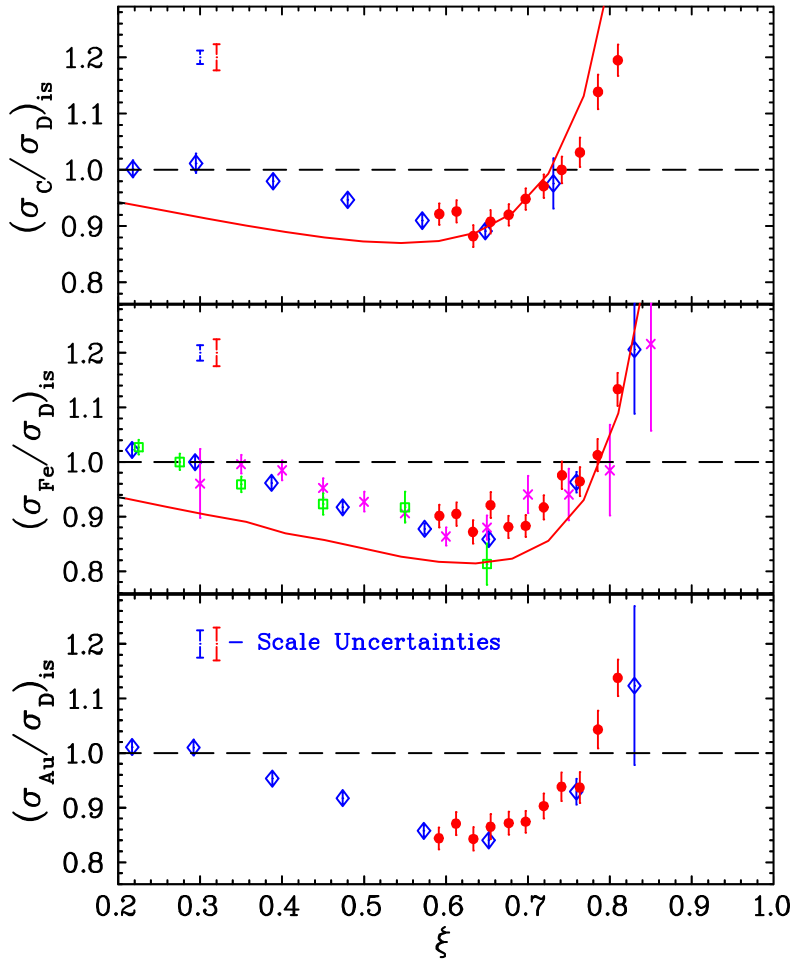
Now Nucleus not Nucleon
Qualitative look at Q-H Duality: e A

- Now **e-nucleus** – individual resonances visible in e-P, somewhat less in e-D and mostly smeared out by e-Fe. Curved line is from MRST global **DIS fits at 10 GeV^2** with **EMC effect** for Fe applied.



Speaking of the EMC Effect….
Found in the eA **Resonance Region**
Further suggestion of Quark-Hadron Duality?

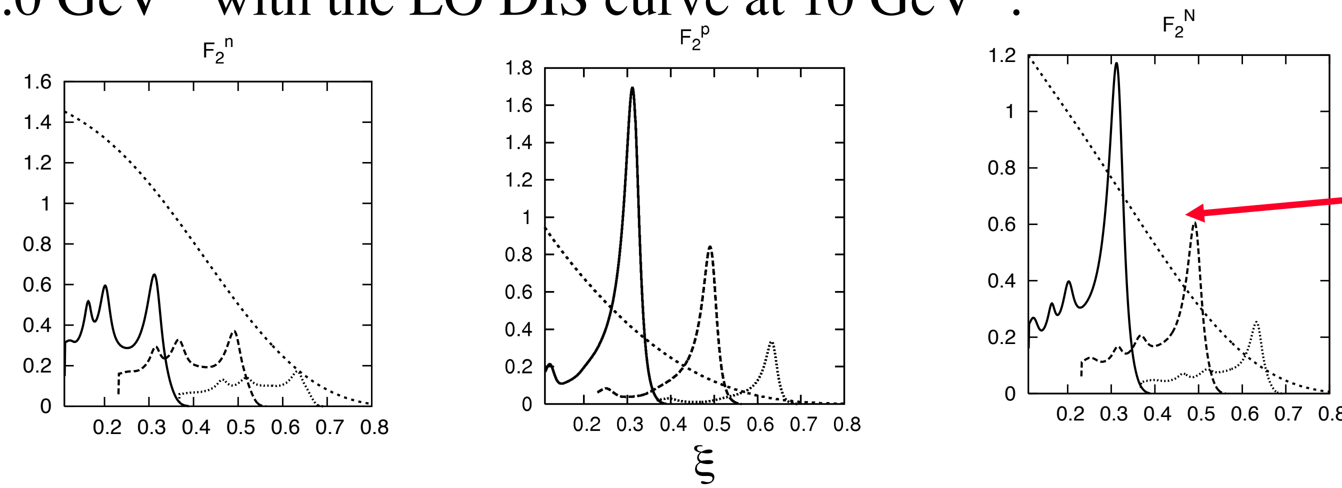
- The solid red circles are Jefferson Lab data taken in the **resonance region $1.2 < W^2 < 3.0$ GeV and $Q^2 = 4$ GeV^2.** All other data points from DIS region.



Now for **Neutrinos -** our "favorite" Rein-Sehgal Model

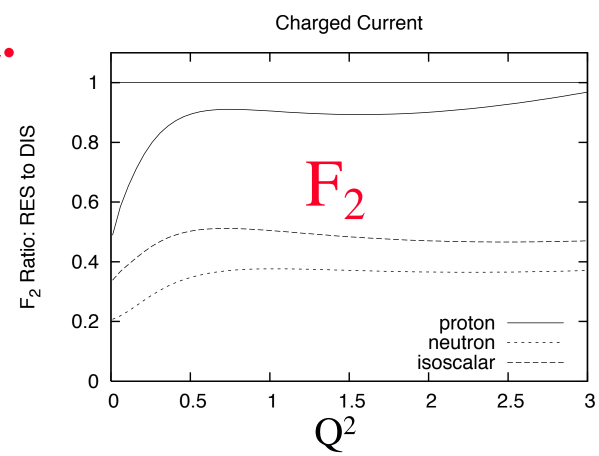
ν-n, ν-p and **ν-N** Resonances (J. Sobczyk et al.-NuWro)

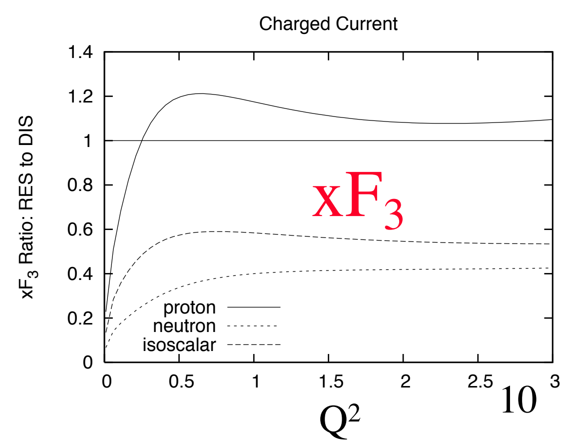
- Comparison to Rein-Sehgal structure functions for n, p and N at $Q^2 = 0.4$, 1.0 and 2.0 GeV^2 with the LO DIS curve at 10 GeV^2 .



However there is reasonable evidence of duality for the region around the Delta with **F_2^N**

- The I integral over the whole W region for the R-S model for resonances off neutron (dotted), proton (solid) and isoscalar (dashed). **No multi-pi resonances and ? non-resonant pi.**





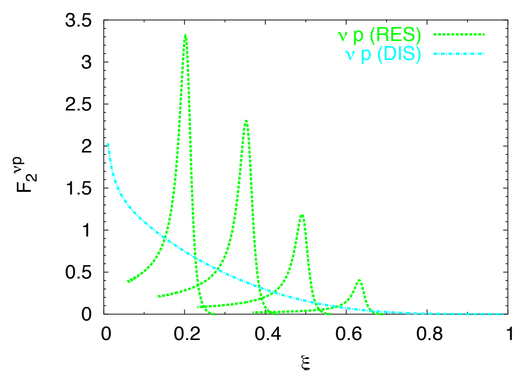
Use alternative models for ν-n, ν-p and ν-N scattering?

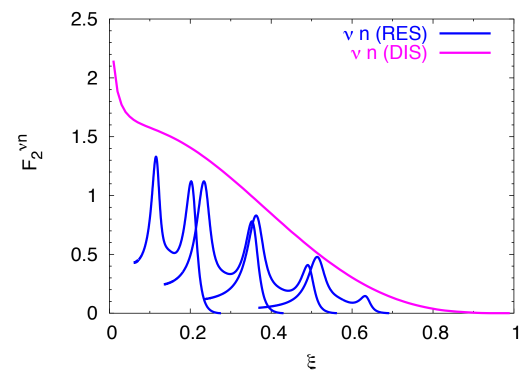
Resonance estimates from Lalakulich, Melnitchouk and Paschos for ν-n and ν-p scattering.

Low-lying resonances: $F_2^{\nu n(res)} < F_2^{\nu p(res)}$, DIS: $F_2^{\nu n(DIS)} > F_2^{\nu p(DIS)}$

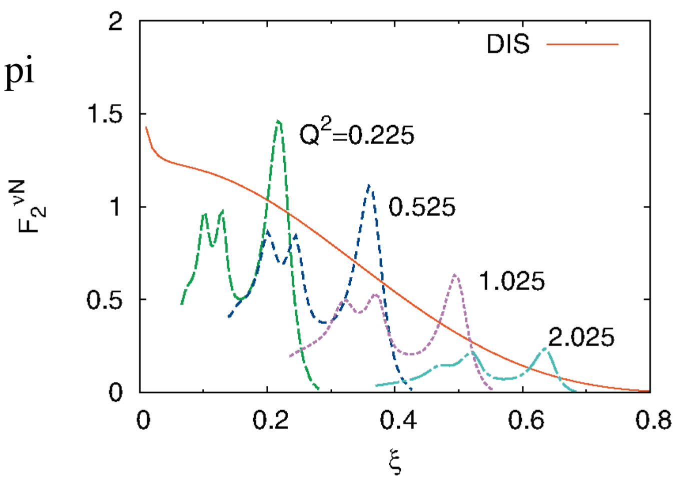
$F_2^{\nu p(res-3/2)} = 3F_2^{\nu n(res-3/2)}$
$F_2^{\nu p(res-1/2)} \equiv 0$

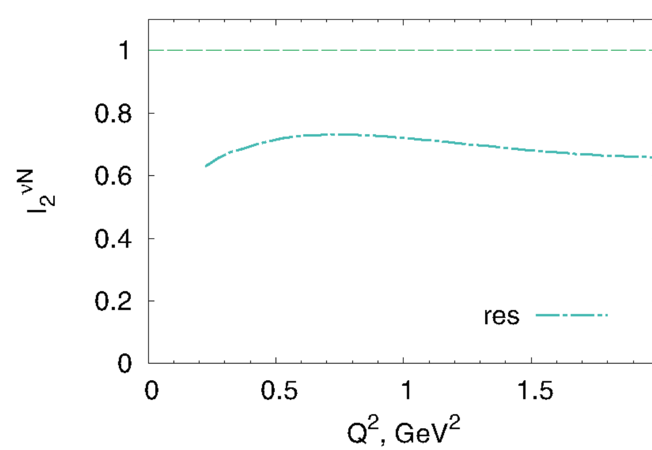
$F_2^{\nu n(res)}$: finite contributions from isospin 3/2 and -1/2 resonances



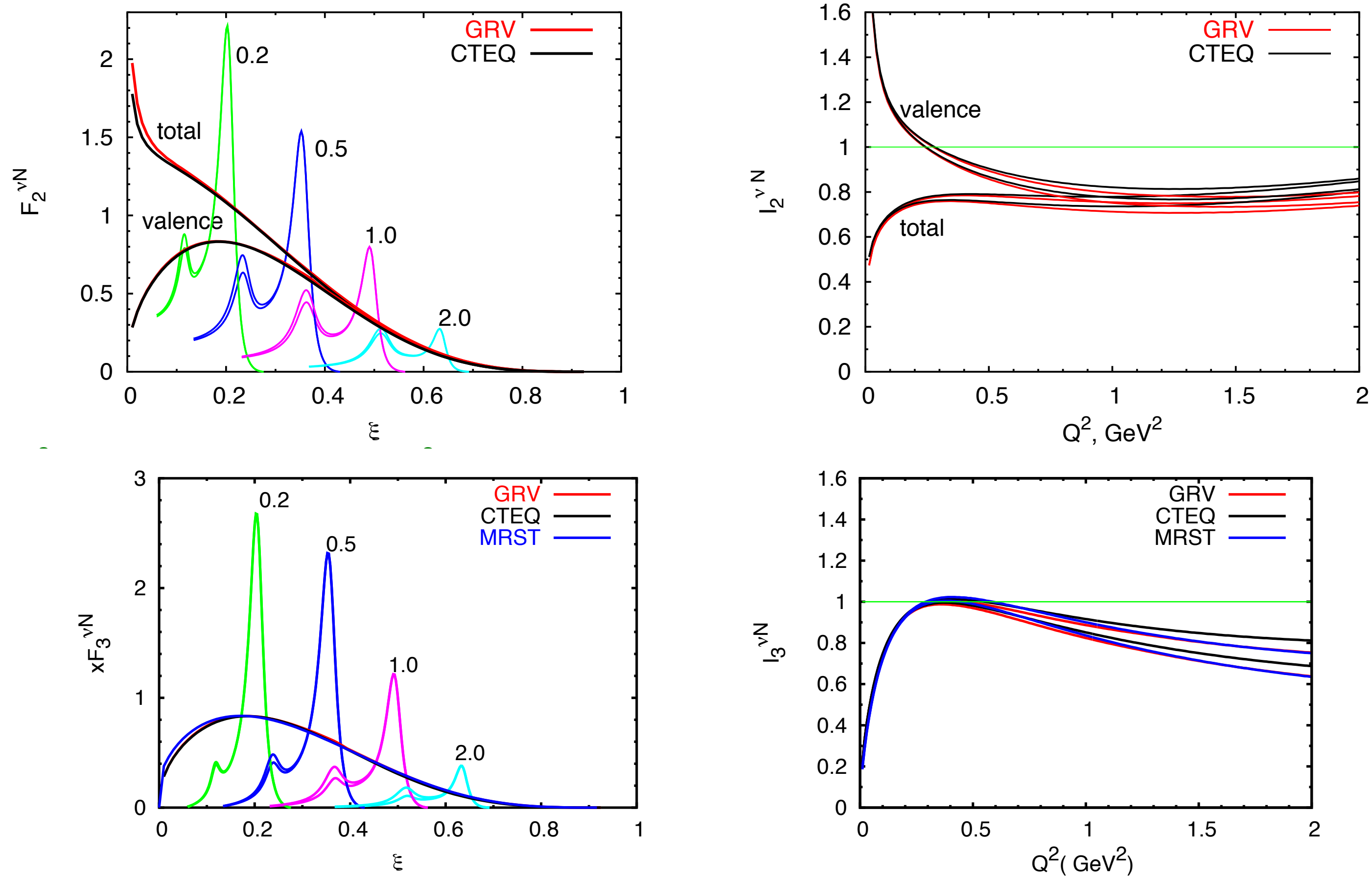


Resonance estimates from GiBUU Model for ν-N scattering.
DIS at 10 GeV^2. No non-resonant pi included





From work of Olga Lalakulich - Local duality appears to holds for the averaged neutrino $F_2^N = (F_2^n + F_2^p) / 2$ (to the 20% level) . Introduce "two-component duality" and resonances dual with valence quarks and non-resonant with sea quarks!!



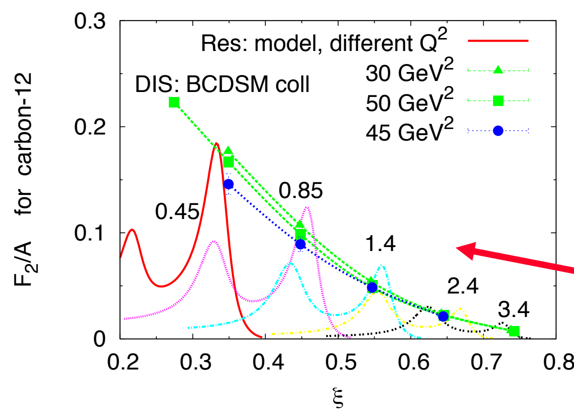
- Global Duality-on the average the resonances appear to oscillate around and slide down the DIS curve. Similar results with the Sato-Lee model
- Local duality in ν-N scattering is worse than in electron scattering: the ratio does not grow appreciably with Q^2

However, it is a different story when talking of NUCLEI not NUCLEON

With the carbon nucleus, equal number of n and p, global duality with incoming electrons is close. Neutrinos not as much … maybe.

For nuclei, the Fermi motion and other medium effects broaden resonances, thus performing averaging

F_2 $^{\nu C}$

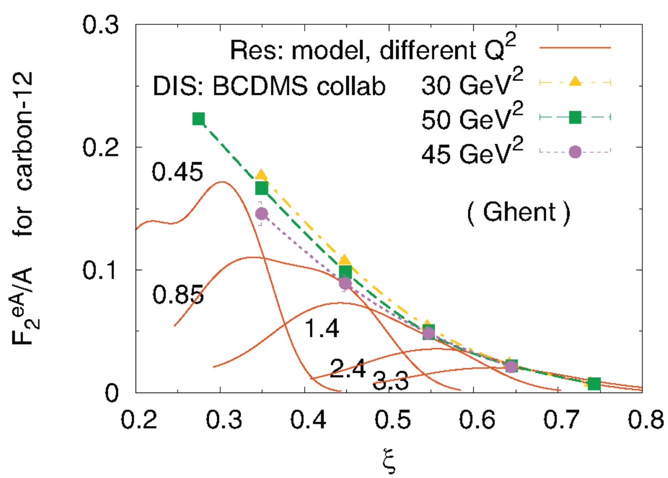


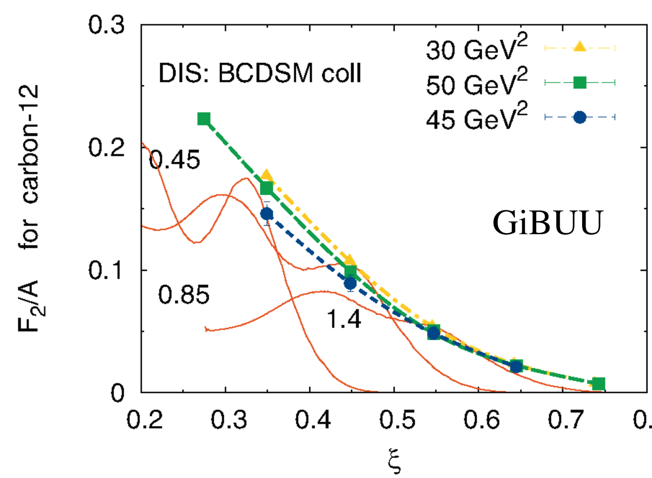
Resonance structure functions: isobar model with phenominological form factors OL,Paschos, PRD 71, 74 includes the first four low-lying baryon resonances $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$

Why are resonances not smeared out for νC as for eC?

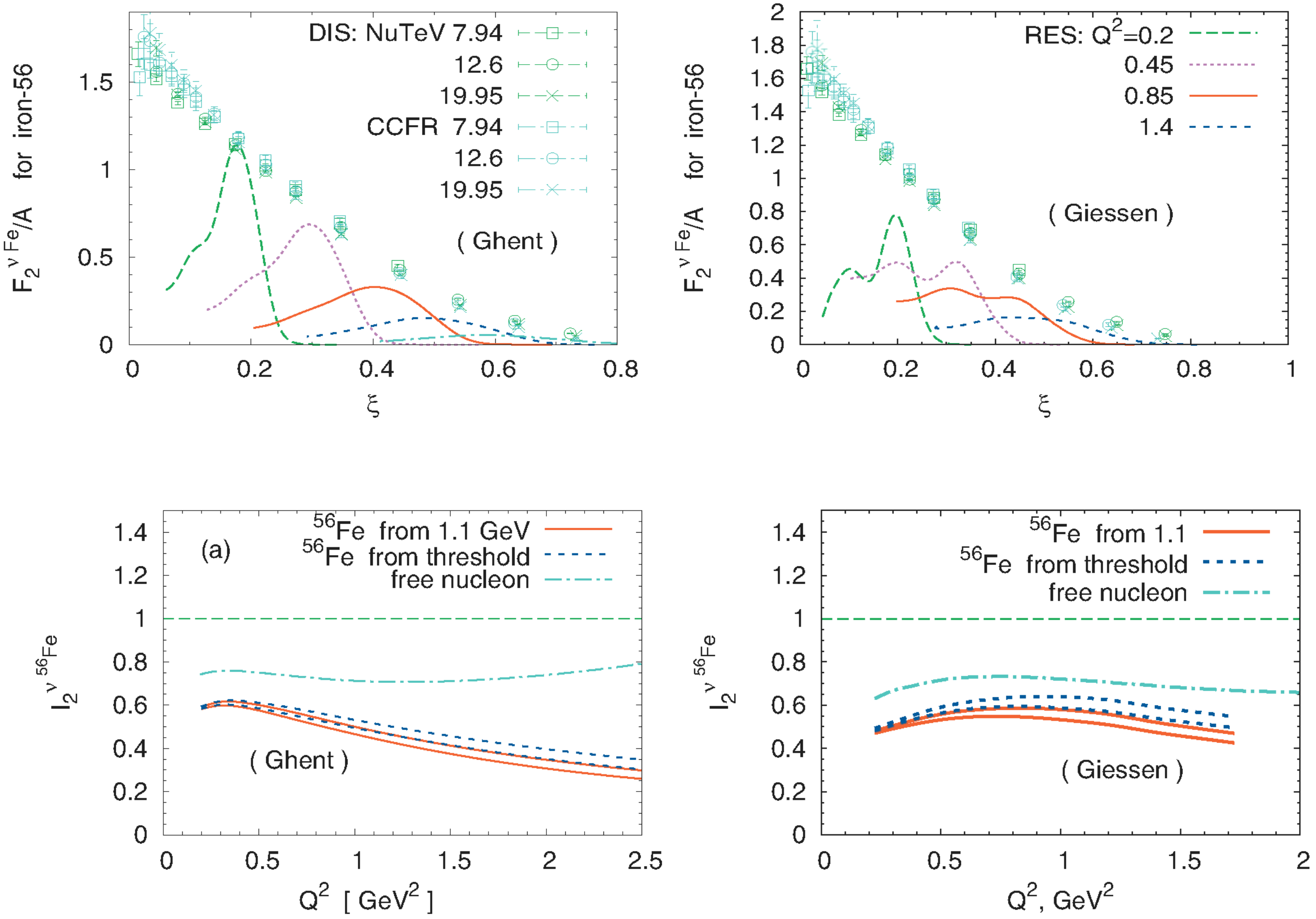
Preliminary!

F_2 ^{eC}



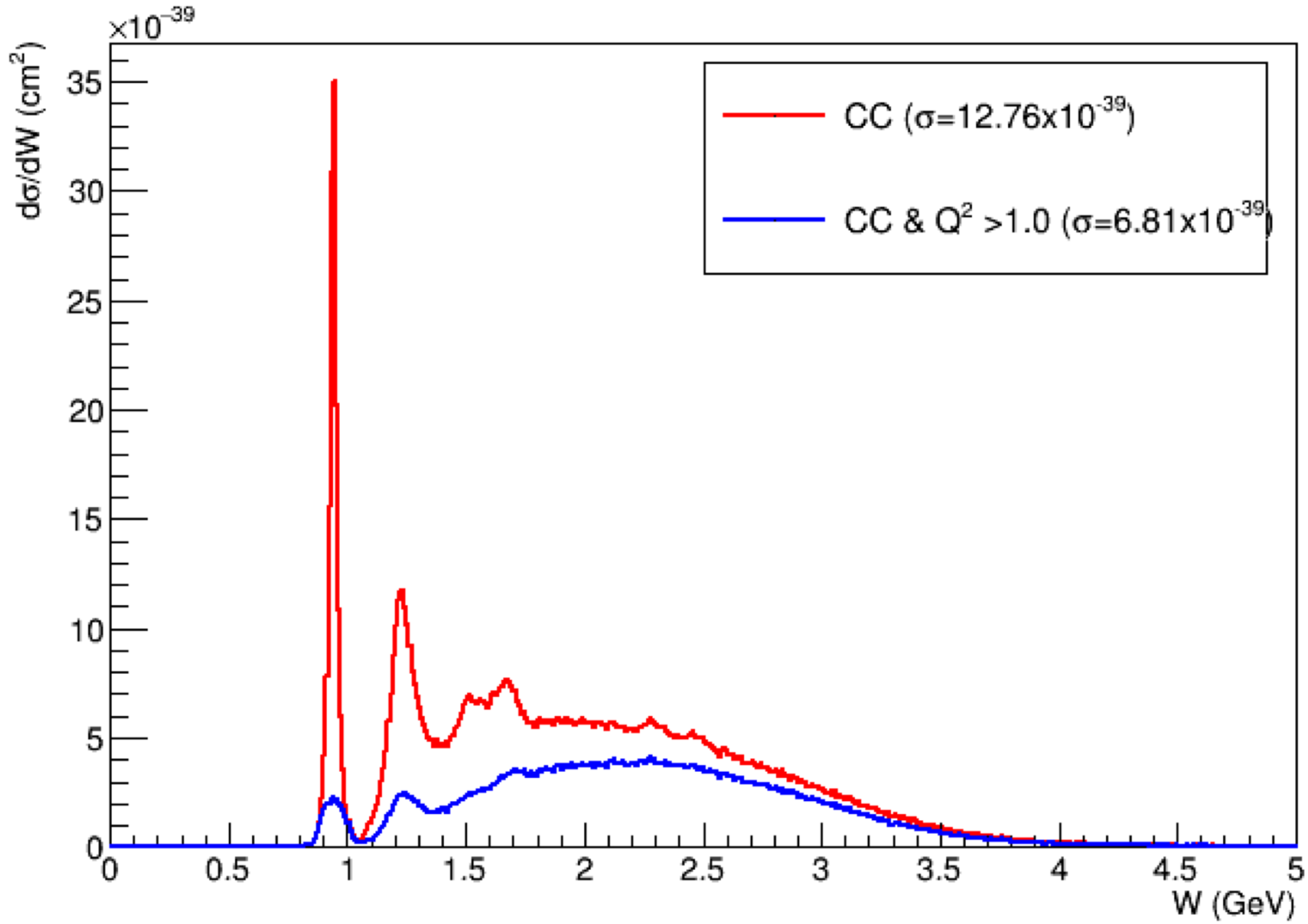


However, for Fe it is a different story - with it's neutron excess?



What about GENIE?

NuMI ME ν beam on Deuterium



Gian Caceres

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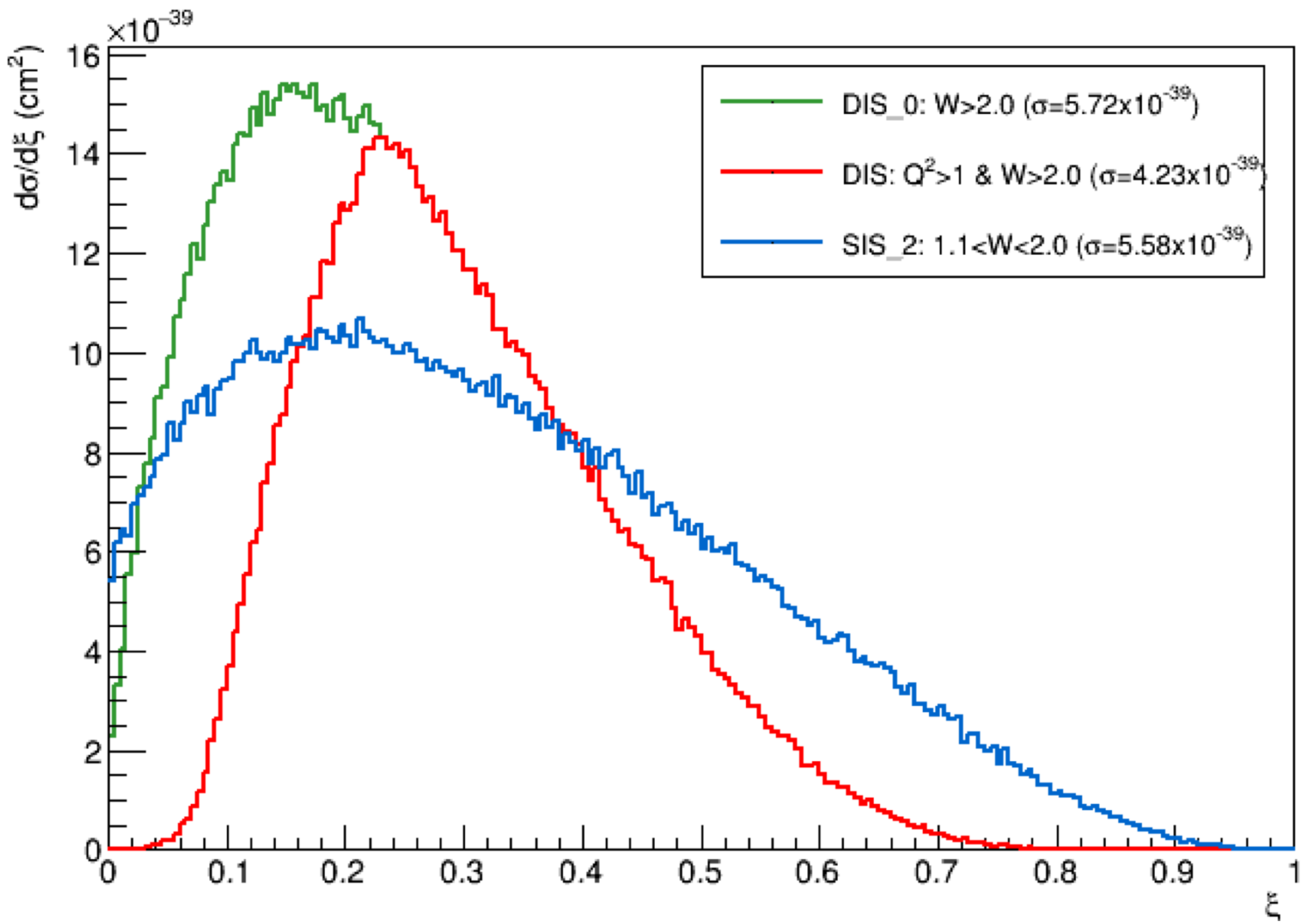


Gian Caceres

Approaching the DIS region, non-perturbative QCD

Essentially unknown experimentally and few theoretical studies.

- $1/Q^2$ effects - when Q is order couple $*M_{N}$, then there are non–perturbative QCD effects that come into play.

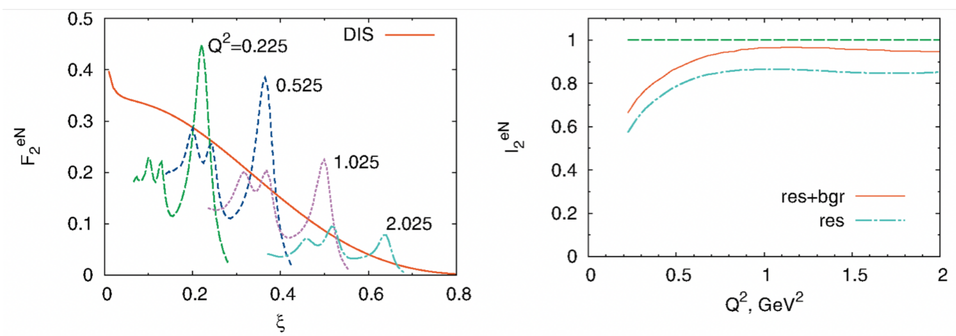
- Called dynamic and kinematic "higher twist" terms such as the (kinematic) target mass effect. These often represent the interaction of multiple quarks or sensitivity to the p_t of quarks. These dynamic higher twist terms are challenging in ν-nucleon and even more complicated in ν-nucleus scattering.

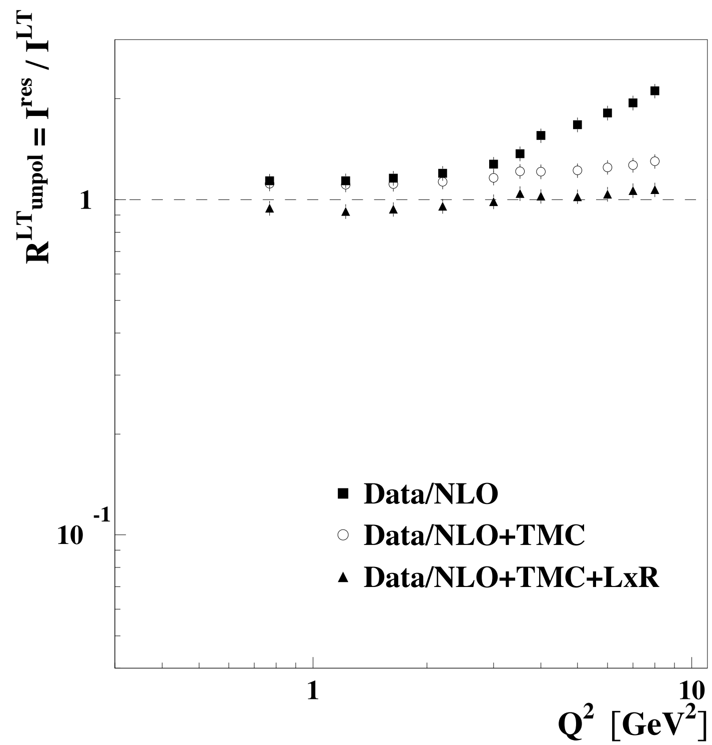
- No recent experimental and limited theoretical studies of these $1/Q^2$ effects with neutrinos.
  - **Twist Four Effects in Deep Inelastic Neutrino Scattering and** Sin2□Theta□wSin2□Theta□w
    S. Fajfer, R.J. Oakes (Sarajevo U. & Northwestern U. & Fermilab). 1985. 2 pp.
    Published in **Fermilab Batavia - FERMILAB-CONF-85-102-T (85,REC.AUG.) 4p**
  - **Twist Four Corrections to Charged and Neutral Current Neutrino Scattering**
    P. Castorina, P.J. Mulders (MIT, LNS). Jun 1984. 16 pp.
    Published in **Phys.Rev. D31 (1985) 2753**
  - **ννN, μμN interactions: Structure functions, higher twist**
    C. Matteuzzi (SLAC). Oct 1981. 13 pp.
    Published in **AIP Conf.Proc. 81 (1982) 186-198**

- **Can we learn about these non-perturbative QCD effects in duality studies?**

Duality and Higher Twist

- Does the fact that duality holds so well for e N resonance scattering compared to LO, **leading twist** DIS results suggest there is little room for higher twist contributions for $Q^2 > 1$ GeV^2 and $x < 0.65$??
- Multiple studies of this available in the literature and all seem to agree with the above statement. For example from: A. Fantoni, N. Bianchi, and S. Liuti. Quark-hadron duality and higher twist contributions in structure functions. *AIP Conf. Proc.*, 747(1):126–129, 2005.





The Bodek-Yang Model

The model incorporates the GRV98 [21] LO parton distribution functions (replacing the variable x with their ξ_w scaling variable) to describe data at high Q^2 and down to 0.8 GeV^2. Below $Q^2 = 0.8$ GeV^2 they take the GRV98 LO PDFs to get the value of $F_2(x, 0.8GeV^2)$ and multiply it by quark-flavor dependent K factors to reach lower Q^2 and W.

For high energy neutrino scattering on quarks and antiquarks, the vector and axial contributions are the same. At very high Q^2, where the quark parton model is valid, both the vector and axial K factors expected to be 1.0. Therefore neutrinos and antineutrino structure functions for an iso-scalar target are given by :

$$\mathscr{F}_2^{\nu}(x,Q^2) = \Sigma_i 2\left[\xi_w q_i(\xi_w,Q^2) + \xi_w \overline{q}_i(\xi_w,Q^2)\right].$$
$$x\mathscr{F}_3^{\nu}(x,Q^2) = \Sigma_i 2\left[\xi_w q_i(\xi_w,Q^2) - \xi_w \overline{q}_i(\xi_w,Q^2)\right].$$

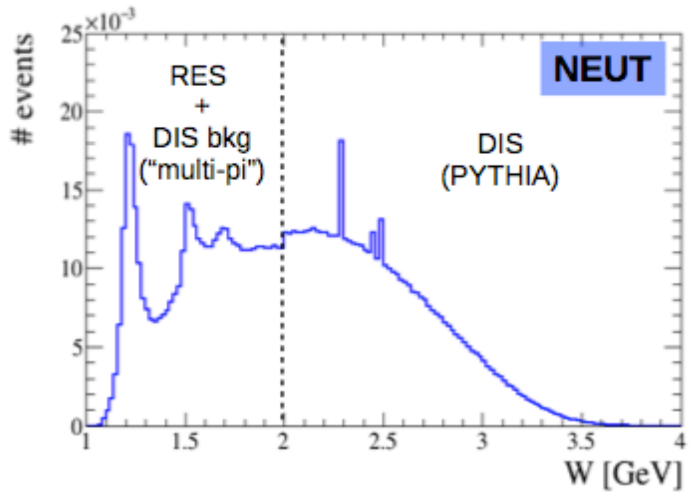
xF_3 are straightforward. Since the vector part of F_2 goes to 0 at $Q^2 = 0$ while the axial component does not, their approach to low-Q^2 must account for this difference in the vector and axial components of F_2. They furthermore account for the differences in higher order QCD effects and scaling violations in F_2 and xF_3 at low-Q^2 and end up with expressions for F_2^{vector}, F_2^{axial} and xF_3 that they than use to predict neutrino nucleon interactions below the DIS region.

$$\mathscr{F}_2^{\nu vector}(x,Q^2) = \Sigma_i K_i^{vector}(Q^2)\xi_w q_i(\xi_w,Q^2) + \Sigma_j K_j^{vector}(Q^2)\xi_w \overline{q}_j(\xi_w,Q^2)$$
$$\mathscr{F}_2^{\nu axial}(x,Q^2) = \Sigma_i K_i^{axial}(Q^2)\xi_w q_i(\xi_w,Q^2) + \Sigma_j K_j^{axial}(Q^2)\xi_w \overline{q}_j(\xi_w,Q^2)$$
$$x\mathscr{F}_3^{\nu}(x,Q^2) = 2H(x,Q^2)\left[\Sigma_i K_i^{xF3}\xi_w q_i(\xi_w,Q^2) - \Sigma_j K_j^{xF3}\xi_w \overline{q}_j(\xi_w,Q^2)\right]$$

Where i denotes $(valence-up)$, $(valence-down)$, $(sea-up)$, $(sea-down)$, and $(sea-strange)$.

1.3. Neutrino Simulation Efforts in the SIS region

Their expressions for this low-Q^2, low-W behavior must, of course, seamlessly blend with the straightforward expressions for F_2 and xF_3 they predict in the DIS region. They then have mimicked the concept of duality but based the extrapolation from the δ to DIS on the described components of their model. There is unfortunately very limited experimental data to compare with their predictions in this low-Q^2, low-W region. However. an indication of a possible problem could be drawn from the earlier quoted recent studies [12] that found the non-resonant background to be considerably smaller than the estimates in GENIE. These estimates in GENIE comes from the BY model prediction of the average strength of the F_2 and xF_3 in this region. Whether this can be related to the duality approach of extrapolating F_2 and xF_3 from the DIS regime down into the resonant region for neutrino scattering has not been explicitly considered. However, we did learn 1.1 that such an extrapolation could indeed lead to overestimating the contribution in the resonant region.

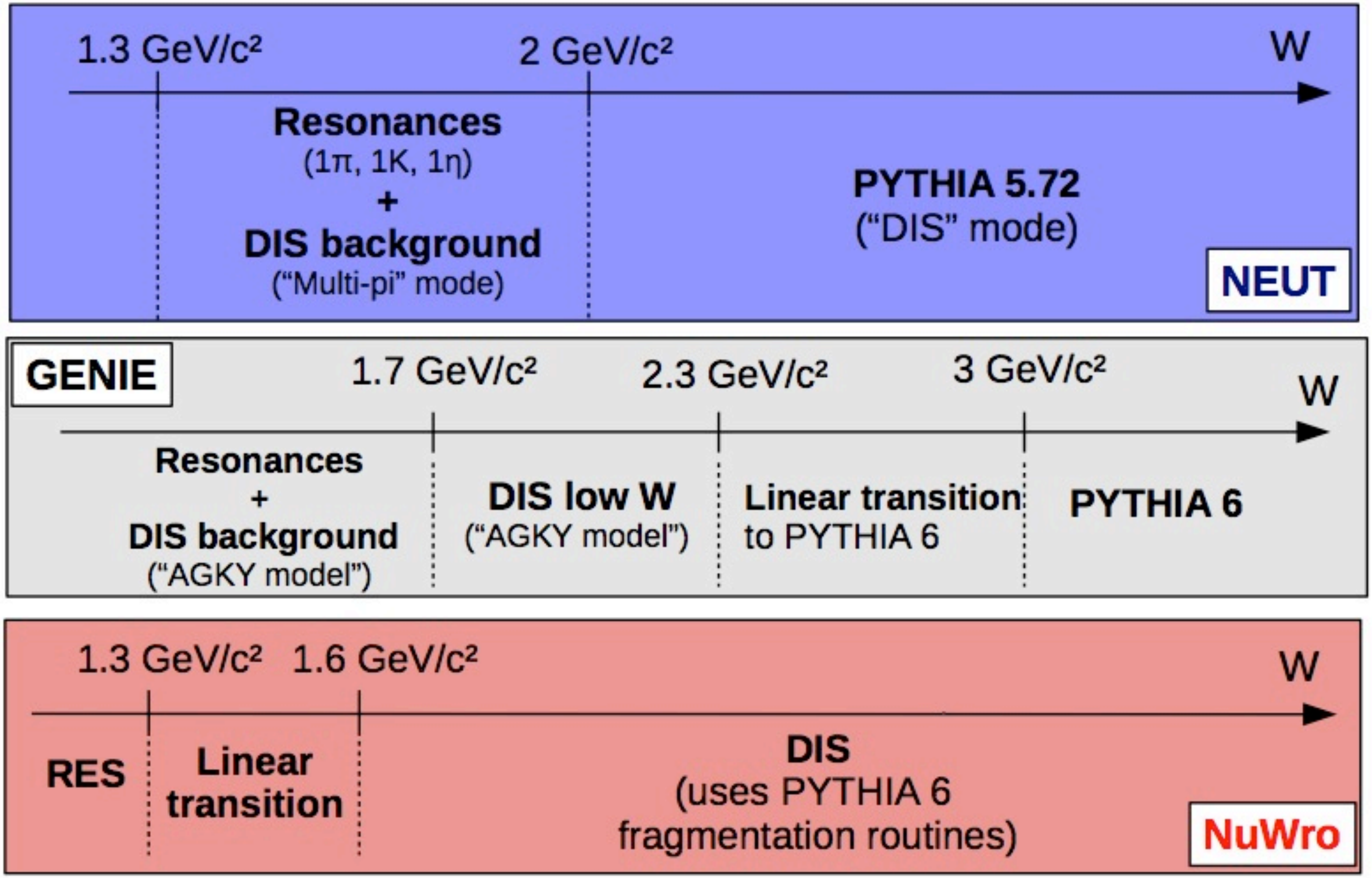


Summary: Quark-Hadron Duality for e-N/A and ν-N/A

- $F_2^{ep\ en}$: Qualitative and quantitative duality HOLDS in electron–nucleon scattering.
- $F_2^{\nu p\ \nu n}$: In neutrino–nucleon scattering, duality roughly holds for the average nucleon but NOT individually for neutron and proton.
- F_2^{eA} : Different story, looks good but quantitative check in e–A not as good as e–n/p .
- ***$F_2^{\nu A}$* : Not at all clear how duality works here, particularly in nuclei with an excess number of neutrons.**
- In general for neutrinos, the resonance structure functions for **proton are much larger than for neutrons** and in the case of DIS structure functions **the situation is opposite.**
- Although to some extent model dependent, a general tendency is that for larger W, DIS structure functions are much larger than the resonance contribution at lower W.
- Can duality be used to suggest problems with current ν-N models via the sum of (1 + n pi) resonance plus non-resonant continuum – try it with GENIE and nuWro,
- There is now fresh suggestions that these so-called DIS nuclear effects **(EMC effect) continue down into the SIS region with W < 2.0 GeV!**
- MINERvA's goal is to make the first experimental measurement of inclusive and (1+n) pion production in the full SIS region.

Additional Details

SIS/DIS Regions in Generators

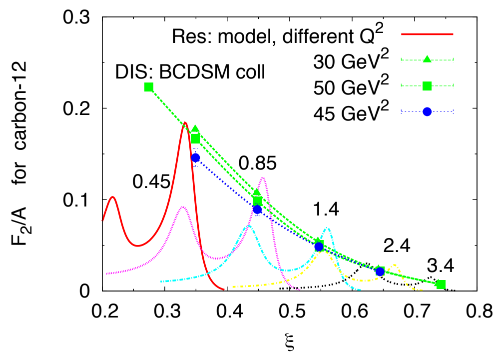


However, it is a different story when talking of NUCLEI not NUCLEON

Even with the carbon nucleus (equal p and n) duality with both incoming electrons and neutrinos has challenges

For nuclei, the Fermi motion and other medium effects broaden resonances, thus performing averaging

Resonance structure functions: isobar model with phenominological form factors OL,Paschos, PRD 71, 74 includes the first four low-lying baryon resonances $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$



Preliminary!

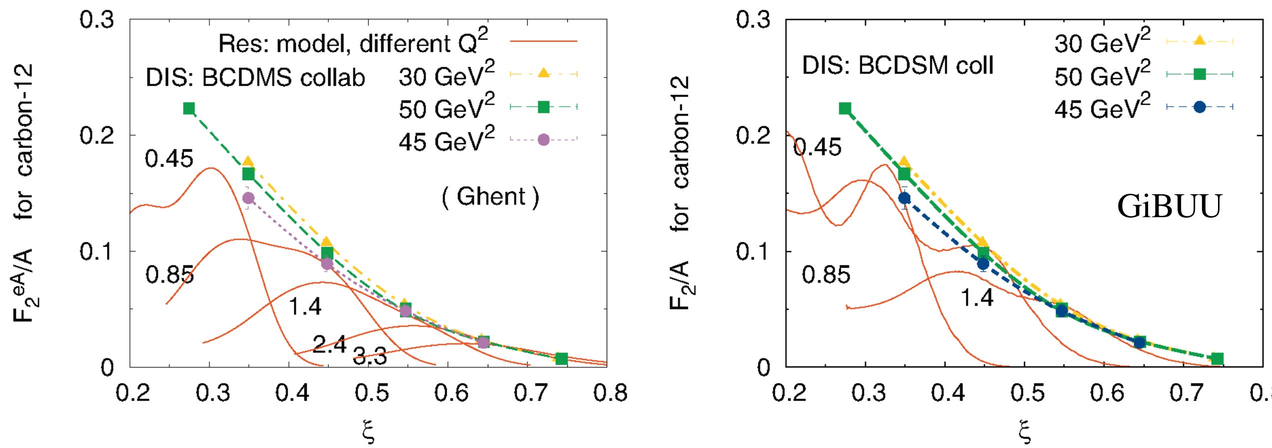
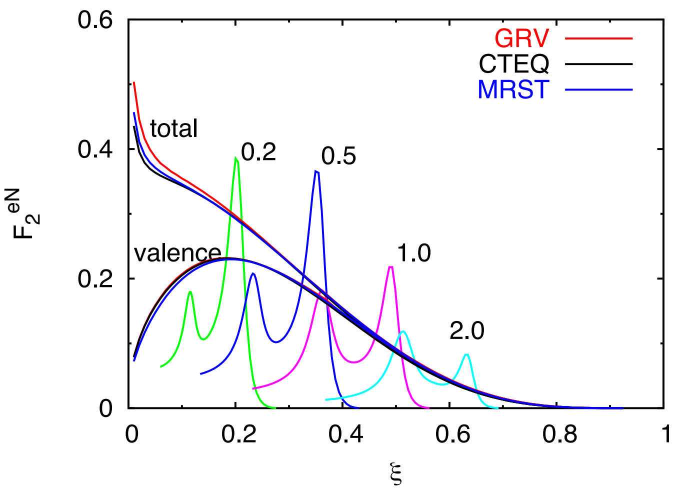
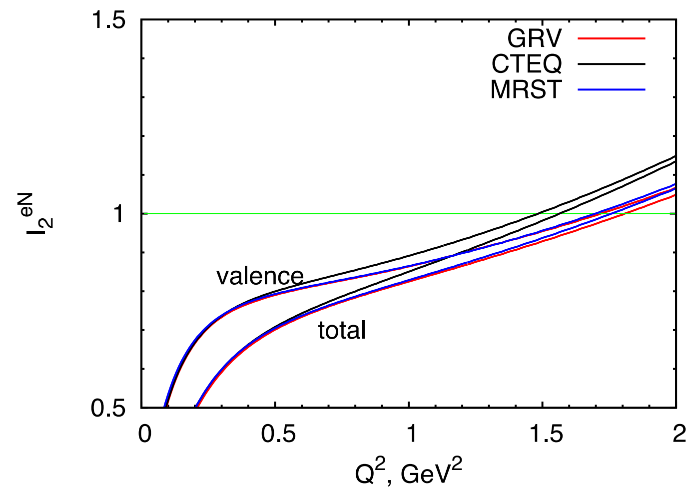


FIGURE 3. (Color online) Resonance curves $F_2^{e^{12}C}/12$ as a function of ξ, for $Q^2 = 0.45, 0.85, 1.4, 2.4$ and 3.3 GeV^2 (indicated on the spectra), obtained within Ghent (left) and Giessen (right) models, compared with the experimental data [23, 24] in the DIS region at $Q^2_{DIS} = 30$, 45 and 50 GeV^2.

Two Component Duality





$Q^2 = 0.2,\ 0.5,\ 1.0,\ 2\ \mathrm{GeV}^2$

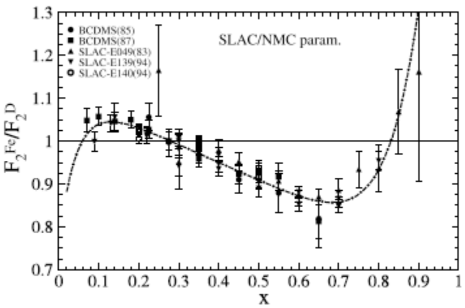
$$\mathcal{I}_{|}(Q^2, Q^2_{DIS}) = \frac{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{RES}(\xi, Q^2)}{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{DIS}(\xi, Q^2_{DIS})}$$

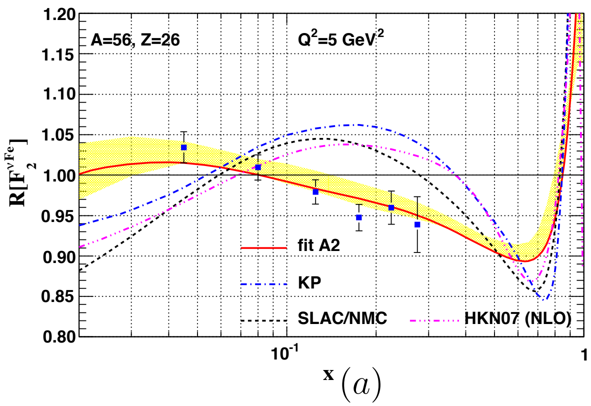
OL,Melnitchouk,Paschos, PRC 75

$$\xi_{\min} = \xi(Q^2, W = 1.6\ \mathrm{GeV}), \qquad \xi_{\max} = \xi(Q^2, W = 1.1\ \mathrm{GeV})$$

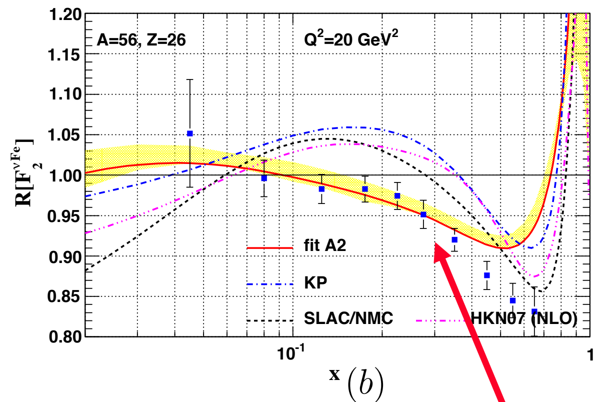
- Two component duality: resonance curves agrees better with the valence–only structure function.
- The resonances are dual to the valence quarks, background (non-resonant) dual to the sea quarks.

Nuclear Correction Factors: ν and $\overline{\nu}$ – $F_2(\nu Fe)$ / $F_2[\nu(n+p)]$

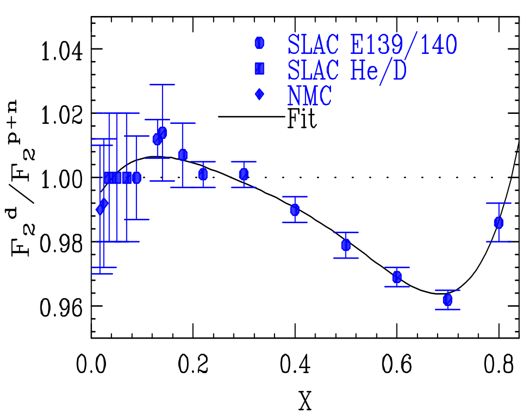


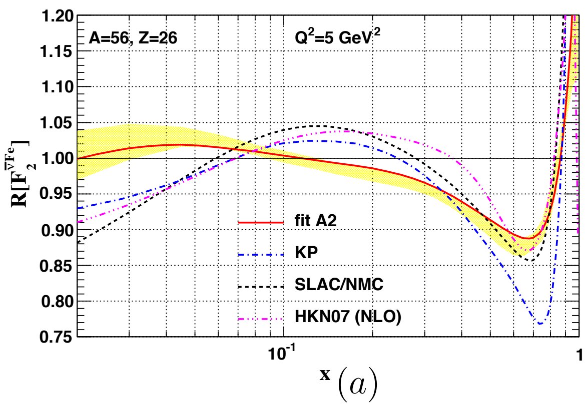


ν

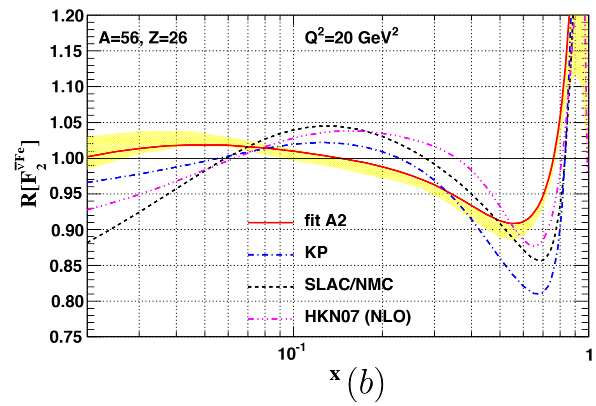


More intense study of medium- high-x region in current round of fits





$\overline{\nu}$

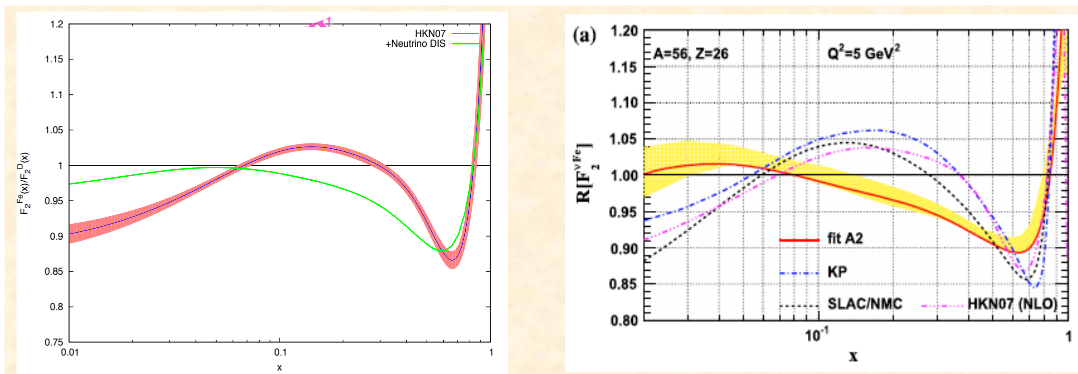


Could NOT find a compromise (χ^2 with tolerance) fit with both ν and e/μ results using cross sections and NuTeV covariant errors.

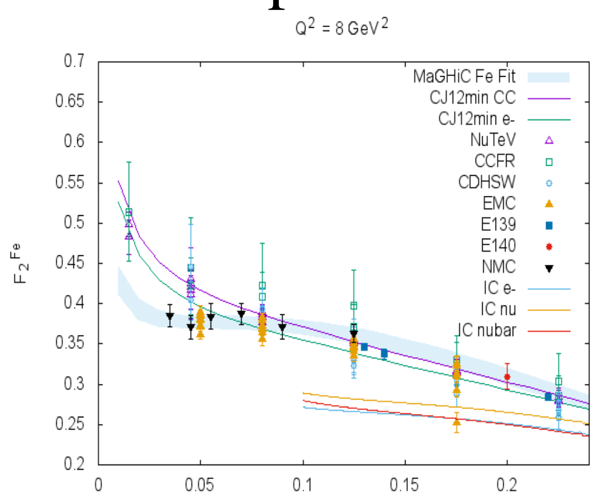
Other Groups find similar results!

Also there are global fitting groups that do NOT find this result.

- Same NCF determined by Japanese Collaboration: Kumano et al.



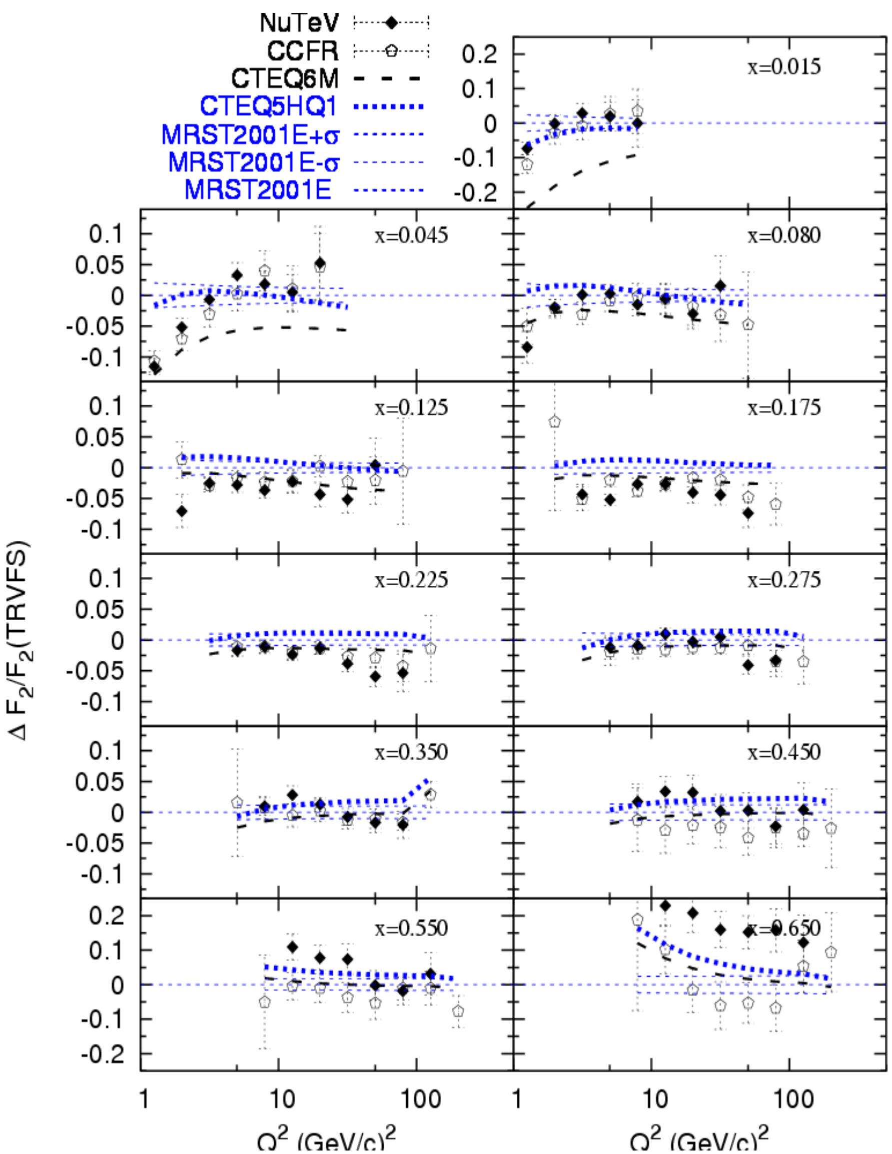
- JLab Centered Collaboration sees same effect looking at measured F_2 (not ratios) from ν Fe compared directly to e Fe. 15% effect.

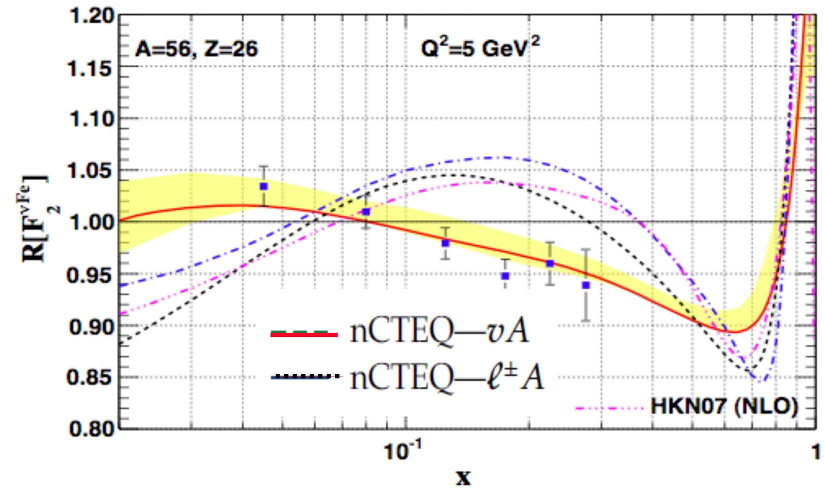


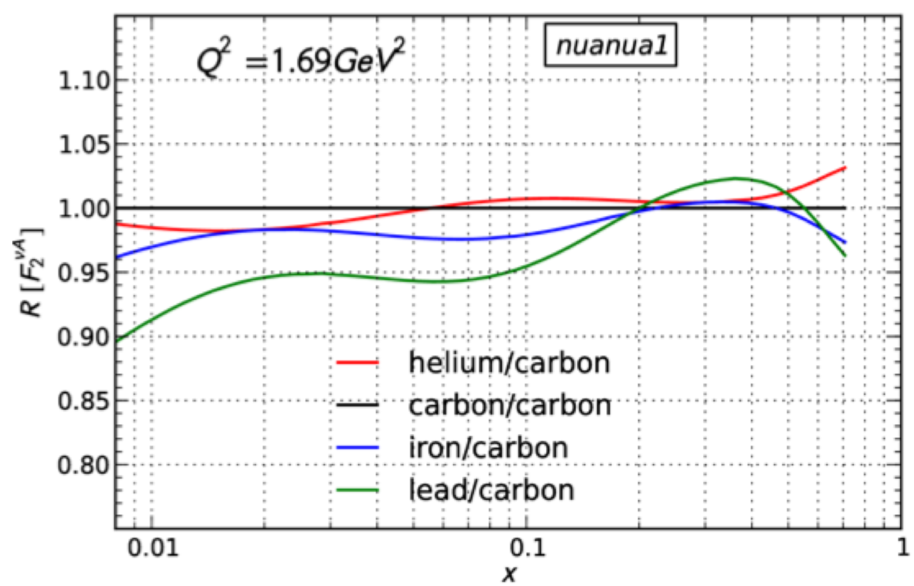
We Now Have A New DIS Player - What does MINERνA see?

Reminder from NuTeV: The Q^2 distribution within an x bin is essential!

An nCTEQ low-Q^2 Prediction for MINERνA

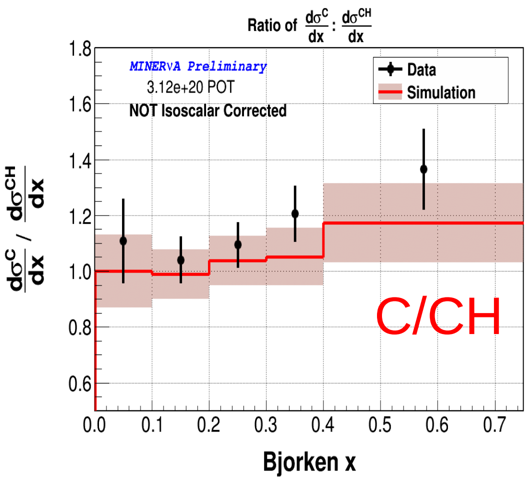


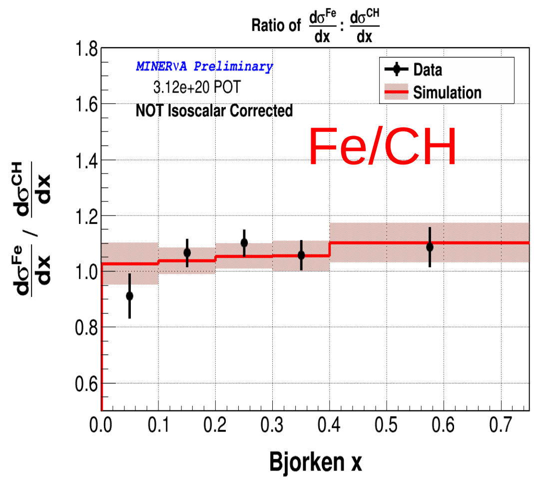


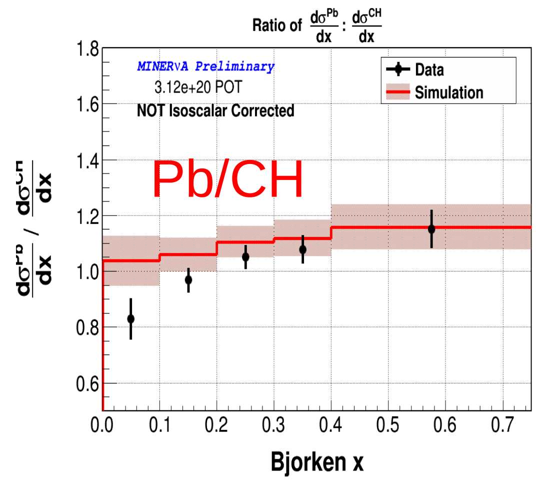


What does MINERνA see? LE DIS Cross Section Ratios – dσ/dx. Much improved ME beam ratios soon to be released!

The Q^2 distribution within an x bin is essential!







J. Mousseau

- The shape of the data at low x, especially with lead is consistent with nuclear shadowing **at <x> = (0.07)** - **where negligible shadowing is expected with e/μ Fe.**
- **nCTEQ fixed low-Q^2 (1.7 GeV^2) points are shown as an example.**